section of [1, Fig. 2], an XY recorder was used to pull a sliding, noncontracting short circuit in a uniform section of waveguide. The recorder was moved in equal increments in the axial direction by a computer, and at each position the real and imaginary outputs of the instrument were read by an A to D converter, and later processed when the average of a predetermined number of scans was available. The data logging was performed with a preset, constant level of confidence [6].

V. Summary

It has been shown that the method of deconvolution of the locating reflectometer is basically different from most applications of deconvolution in that the information available is strictly band limited, i.e. high (and low) frequencies are lost in the "recording" and not in the "playback." Although in this case only a modest improvement in resolution may be expected, the results show cases when the effort was worthwhile. Use was made of the fact that the real and imaginary parts of the data, i.e., the locating plots, are a Hilbert transform pair, and thus one measurement resulted in two independent deconvolutions, one obtained from the real, the other from the imaginary parts only. The results are averaged, improving the signal-to-noise ratio. This method makes the results insensitive to gain differences and to the lack of exact phase quadrature between the real and imaginary parts.

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Shot-Noise in Resistive-Diode Mixers and the Attenuator Noise Model

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***Abstract*—The representation of a pumped exponential diode, operating as a mixer, by an equivalent lossy network, is reexamined. It is shown that the model is correct provided the network has ports for all sideband frequencies at which (real) power flow can occur between the diode and its embedding. The temperature of the equivalent network is $\eta/2$ times the physical temperature of the diode. The model is valid only if the series resistance and nonlinear capacitance of the diode are negligible. Expressions are derived for the input and output noise temperature and the noise–temperature ratio of ideal mixers. Some common beliefs concerning noise–figure and noise–temperature ratio are shown to be incorrect.**

I. Introduction

In recent years, the need for low-noise mixers, especially in the field of millimeter-wave radio astronomy, has stimulated a considerable amount of research into the theory and design of mixers and mixer diodes. Improved mixer designs have revealed a substantial discrepancy [1] between measured noise performance and that predicted by the simple attenuator noise model of the mixer.

In the attenuator noise model, the mixer is represented as a lossy network whose port-to-port power loss is equal to the mixer conversion loss, and whose physical temperature T_A accounts for the mixer noise. Uncertainty has existed concerning the value of T_A. One widely held belief is that the output noise–temperature ratio[1] t_M of the mixer should be close to unity, from which it follows that T_A is equal to the physical temperature T of the mixer, and that the noise figure of a room-temperature mixer is equal to its conversion loss. An alternative view is that t_M is equal

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[1]The noise–temperature ratio t_M of a mixer is defined as [2] (the available IF output noise power in bandwidth $\Delta f)\div(kT\Delta f)$, when the mixer and all its input terminations are maintained at ambient temperature T.

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to the time average of the noise–temperature ratio[2] t_D of the dc-biased diode, usually close to 0.5. Neither of these agrees well with measured mixer noise, particularly at the shorter microwave and millimeter wavelengths.

The theory of shot-noise in mixers was first examined by Strutt [4] and more recently by van der Ziel and Watters [5], van der Ziel [6], and Kim [7], all of whom considered two- or three-frequency mixer models. Dragone [8] extended this work, deriving a general expression for the correlation between various frequency components of the shot-noise in a pumped diode, and showed that an ideal pumped diode is equivalent to a lossy multiport network at a constant temperature. Saleh [9] used this to examine the noise behavior of mixers with exponential diodes and reactive terminations at all sideband frequencies above the signal and image.

The observed discrepancies between measured mixer noise and that predicted by the three-port attenuator model have recently been studied by Held and Kerr, [10], [11] and shown to have three main causes: 1) the time-varying diode admittance, generally complex, acting on correlated components of the time-varying shot-noise of the diode, 2) lossy terminations at higher sidebands, and 3) appreciable series resistance in the diode. Scattering effects in the semiconductor material were also shown to cause a slight increase in the noise of room-temperature mixers.[3]

In this paper, the general mixer theory of Held and Kerr is used to investigate the noise behavior of ideal mixers and the validity of some widely held ideas about mixer noise. An ideal exponential diode is assumed, having full shot-noise but negligible series resistance and nonlinear junction capacitance.[4] It is shown that, in agreement with Dragone [8] and Saleh [9], such an ideal diode, operated as a mixer, is equivalent to a lossy network at a temperature T_A. The equivalent network has ports for all sideband frequencies at which (real) power flow can occur between the diode and its embedding. The temperature T_A is shown to be $\eta T/2$, where η is the ideality factor of the diode and T is its physical temperature. Such a noise model has practical applications at lower microwave frequencies where Schottky diodes are available with low series resistance and small capacitance and where the embedding impedance is well defined up to several harmonics of the LO. At very low frequencies, below $\sim$1 MHz, $1/f$-noise will become significant, thereby invalidating the simple model. At frequencies where the nonlinear diode capacitance has a significant susceptance, parametric effects will be present, and a more general analysis is required.

[2]The noise–temperature ratio t_D of a dc-biased diode is defined as [3] (the available IF output noise power in bandwidth $\Delta f)\div(kT\Delta f)$, when the diode is at physical temperature T.

[3]Other investigations of noise in millimeter-wave mixers have been made recently by Fei and Mattauch [12] and Keen [13].

[4]The diode may have finite *static* capacitance, which can be regarded as part of the embedding circuit for purposes of analysis.

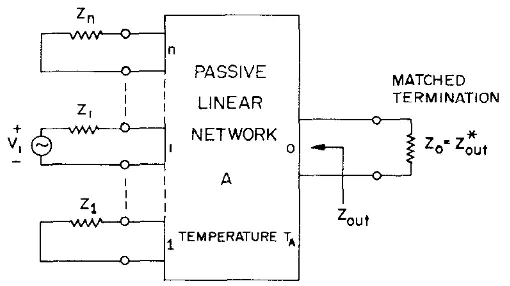

Fig. 1. Passive linear network at temperature T_A.

II. The Attenuator Noise Model

In this section, the noise properties of a passive linear multiport network will be examined. It will be shown in Section IV that the noise behavior of a certain class of pumped mixer diodes can be described by such a multiport network or attenuator.

Consider the passive linear multiport A, shown in Fig. 1, to be terminated at ports 1 to n by impedances Z_i. The output port 0 is conjugate-matched with impedence $Z_0 = Z^*_{out}$. The loss L_i from any port i to the output is defined as

$$L_i = \frac{\text{power available from source } (V_i \text{ and } Z_i)}{\text{power from } V_i \text{ delivered to load } Z_0}. \quad (1)$$

This is analogous to the conversion loss of a mixer with a matched output termination.

Let the network A and all its terminations be maintained at a temperature T_A. Then, for thermal equilibrium, the available noise power in a narrow band Δf at the output port is

$$P_{0_{\text{avail}}} = kT_A\Delta f. \quad (2)$$

This is the sum of thermal noise contributions from each of the terminations Z_i $(i=1,\cdots,n)$ and a contribution P' from the network A itself:

$$P_{0_{\text{avail}}} = P' + \sum_{i=1}^{n} \frac{kT_A\Delta f}{L_i}. \quad (3)$$

With (2), this gives

$$P' = kT_A\left[1 - \sum_{i=1}^{n} \frac{1}{L_i}\right]\Delta f. \quad (4)$$

P' is the available noise power at the output port 0 of network A when all the input terminations Z_i $(i=1,\cdots,n)$ are held at absolute zero temperature.

For the more general case, with the network A at temperature T_A and the terminations Z_i at temperature T_E, the available output power at port 0 is

$$P_{0_{\text{avail}}} = k\Delta f\left\{T_A\left[1 - \sum_{i=1}^{n} \frac{1}{L_i}\right] + T_E\sum_{i=1}^{n} \frac{1}{L_i}\right\}. \quad (5)$$

It will be shown below that, for a certain class of mixer diode, there exists a noise-equivalent passive linear network whose output noise is described by an equation similar to (5), with T_A determined only by the physical temperature and ideality factor of the diode.

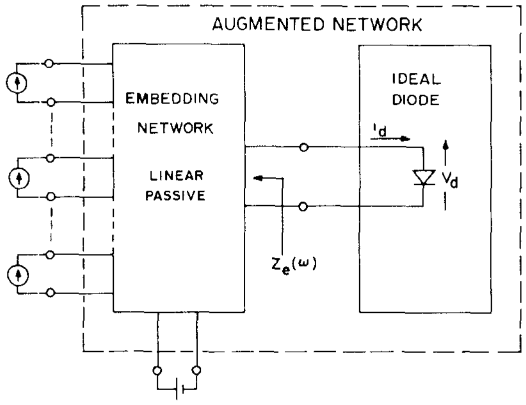

Fig. 2. The ideal diode connected to its linear passive embedding network, which together comprise the augmented network (broken line). All sources are external to the augmented network.

III. Outline of Mixer Theory

The mixer theory of Held and Kerr [10], [11] is used here to study the noise power flow at the terminals of an ideal exponential diode embedded in a linear passive network and pumped by an arbitrary local oscillator waveform. The ideal diode has zero nonlinear capacitance and series resistance and exhibits full shot-noise.

The diode current and voltage are related by

$$i_d = i_0[\exp(\alpha v_d) - 1] \tag{6}$$

where

$$\alpha = q/\eta kT. \tag{7}$$

The incremental conductance of the diode

$$g(i) = \frac{di_d}{dv_d} \cong \alpha i. \tag{8}$$

When the diode is biased at a dc current i, the shot-noise is given by the standard shot-noise equation:

$$\langle \delta i_n^2 \rangle = 2qi\Delta f. \tag{9}$$

The diode is connected to the passive linear embedding network which includes all external source and load impedances, as shown in Fig. 2. Local oscillator power applied to the mixer produces a periodic current waveform at the diode

$$i_d(t) = \sum_{m=-\infty}^{\infty} I_m \exp jm\omega_p t, \qquad I_{-m} = I_m^*. \tag{10}$$

The corresponding diode conductance waveform is

$$g(t) = \sum_{m=-\infty}^{\infty} G_m \exp jm\omega_p t, \qquad G_{-m} = G_m^*. \tag{11}$$

It follows from (8) that

$$I_m = G_m/\alpha. \tag{12}$$

In analyzing the small-signal and noise behavior of the mixer diode, the concise subscript notation of Saleh [9] is used to denote the various sideband frequencies: if ω_p and ω_0 are the local oscillator and intermediate (angular) frequencies, then ω_m denotes sideband frequency $\omega_0 + m\omega_p$. Thus ω_1, ω_{-1}, and ω_2 are the upper sideband, lower sideband, and sum frequencies. The small-signal behavior of the diode is described by a conversion admittance matrix $\boldsymbol{Y}$ relating currents and voltages δI_m and δV_m at all the sideband frequencies ω_m. Thus

$$\boldsymbol{\delta I} = \boldsymbol{Y\delta V} \tag{13}$$

where

$$\boldsymbol{\delta V} = \{\cdots, \delta V_m, \cdots, \delta V_1, \delta V_0, \delta V_{-1}, \cdots\}^T$$
$$\boldsymbol{\delta I} = \{\cdots, \delta I_m, \cdots, \delta I_1, \delta I_0, \delta I_{-1}, \cdots\}^T$$

and

$$\boldsymbol{Y} = \begin{array}{c|c} \text{row \#} & \\ \begin{array}{c} \vdots \\ 1 \\ 0 \\ -1 \\ \vdots \end{array} & \begin{bmatrix} & \vdots & \vdots & \vdots & \\ \cdots & Y_{11} & Y_{10} & Y_{1-1} & \cdots \\ \cdots & Y_{01} & Y_{00} & Y_{0-1} & \cdots \\ \cdots & Y_{-11} & Y_{-10} & Y_{-1-1} & \cdots \\ & \vdots & \vdots & \vdots & \end{bmatrix} \\ & \begin{array}{ccccc} \cdots & 1 & 0 & -1 & \cdots \end{array} \\ & \text{column \#} \end{array}$$

where [3]

$$Y_{mn} = G_{m-n}. \tag{14}$$

It follows from the Y matrix that the pumped diode can be represented as a multiport network with one port for each sideband frequency, as shown in Fig. 3. Each port is connected to its embedding impedance $Z_{e_m} = Z_e(\omega_0 + m\omega_p)$.

The embedded diode is represented by the augmented network outlined by the broken line in Figs. 2 and 3. In normal mixer operation, all ports of the augmented network are open-circuited or connected to signal or noise current sources. For the augmented network

$$\boldsymbol{\delta I'} = \boldsymbol{Y'\delta V} \tag{15}$$

where

$$\boldsymbol{Y'} = \boldsymbol{Y} + \mathbf{diag}\{\cdots, 1/Z_{e_m}, \cdots\}. \tag{16}$$

Inverting (15) gives

$$\boldsymbol{\delta V} = \boldsymbol{Z'\delta I'} \tag{17}$$

where

$$\boldsymbol{Z'} = (\boldsymbol{Y'})^{-1}. \tag{18}$$

The small-signal properties of the mixer can be deduced from (17).

If the conversion loss from any sideband ω_m to the IF ω_0 is defined as L_m = (signal power at sideband ω_m available to the diode from the embedding network)/(downconverted signal power available at ω_0 to the embedding network from the diode), then it follows from (17) and Fig. 2 that

$$L_m = \frac{1}{4|Z'_{0m}|^2} \frac{|Z_{e_m}|^2}{\text{Re}[Z_{e_m}]} \frac{|Z_{e_0}|^2}{\text{Re}[Z_{e_0}]}. \tag{19}$$

The mean-square output noise voltage due to shot-noise

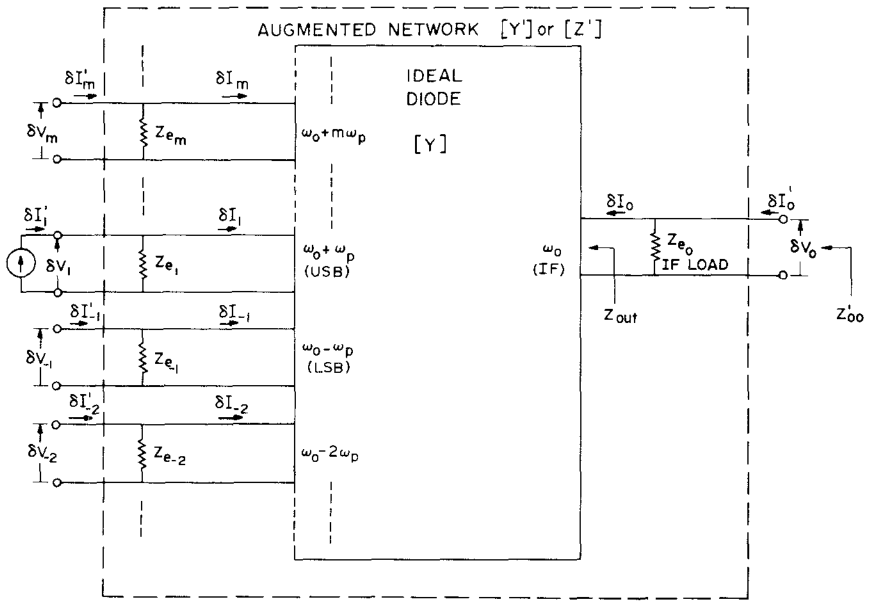

Fig. 3. Frequency-domain representation of the mixer. The diode is represented as the inner multiport network, characterized by conversion admittance matrix $\boldsymbol{Y}$. The complete mixer is represented by the augmented network (broken line), which includes all embedding impedances Z_{e_m}, but excludes all sources, and is described by the augmented matrices $\boldsymbol{Y}'$ or $\boldsymbol{Z}'$.

in the diode is given by[5]

$$\langle \delta V_{n_0}^2 \rangle = \boldsymbol{Z}_0' \boldsymbol{C} \boldsymbol{Z}_0'^{\dagger} \tag{20}$$

where $\boldsymbol{Z}_0'$ is the center row of matrix $\boldsymbol{Z}'$ and $\boldsymbol{C}$ is the shot-noise correlation matrix given by [8]

$$C_{mn} = 2qI_{m-n}\Delta f \tag{21}$$

where I_{m-n} is the $(m-n)$th Fourier coefficient of the LO current in the diode as defined in (10). Note that (20) does not include the effects of thermal noise in the embedding network.

If the output of the mixer is conjugate-matched, $Z_{out} = Z_{e_0}^*$. Then the central element of the matrix $\boldsymbol{Z}'$ is (see Fig. 3)

$$Z'_{00} = \left[\frac{1}{Z_{e_0}} + \frac{1}{Z_{out}} \right]^{-1} = \frac{|Z_{e_0}|^2}{2\,\mathrm{Re}\left[Z_{e_0}\right]}. \tag{22}$$

Equations (18)–(22) are the basis for the following noise analysis.

IV. Shot-Noise in the Resistive-Diode Mixer

In this section, it will be shown that the shot-noise equation (20) for a pumped exponential diode implies an equivalent lossy network with the same noise and conversion properties as the diode. The equivalent temperature T_L of this network depends only on the physical temperature T of the diode, and its ideality factor η.

From (7), (8), (16), and (21), we have

$$\boldsymbol{C} = 2\eta kT\Delta f \boldsymbol{Y} \tag{23}$$

$$= 2\eta kT\Delta f[\boldsymbol{Y}' - \boldsymbol{D}] \tag{24}$$

where

$$\boldsymbol{D} = \mathbf{diag}\left\{ \cdots, 1/Z_{e_m}, \cdots \right\}. \tag{25}$$

Now form the product $\boldsymbol{Z}'\boldsymbol{C}\boldsymbol{Z}'^{\dagger}$ in two stages. First, using (18) and (24)[6],

$$\boldsymbol{Z}'\boldsymbol{C} = 2\eta kT\Delta f[\boldsymbol{Z}'\boldsymbol{Y}' - \boldsymbol{Z}'\boldsymbol{D}] \tag{26}$$

$$= 2\eta kT\Delta f[\boldsymbol{I} - \boldsymbol{Z}'\boldsymbol{D}]. \tag{27}$$

Then post-multiply by $Z'^{\dagger}$ to obtain the square matrix

$$\boldsymbol{Z}'\boldsymbol{C}\boldsymbol{Z}'^{\dagger} = 2\eta kT\Delta f[\boldsymbol{Z}'^{\dagger} - \boldsymbol{Z}'\boldsymbol{D}\boldsymbol{Z}'^{\dagger}]. \tag{28}$$

The center element of this matrix is, from (20), $\boldsymbol{Z}_0'\boldsymbol{C}\boldsymbol{Z}_0'^{\dagger} = \langle \delta V_{n_0}^2 \rangle$.

Therefore,

$$\langle \delta V_{n_0}^2 \rangle = 2\eta kT\Delta f \left\{ Z_{00}'^{*} - \sum_m |Z'_{0m}|^2 \frac{1}{Z_{e_m}} \right\}. \tag{29}$$

Using (22),

$$\langle \delta V_{n_0}^2 \rangle = \eta kT\Delta f \frac{|Z_{e_0}|^2}{\mathrm{Re}\left[Z_{e_0}\right]} \cdot \left\{ 1 - 2\sum_m \frac{|Z'_{0m}|^2}{Z_{e_m}} \frac{\mathrm{Re}\left[Z_{e_0}\right]}{|Z_{e_0}|^2} \right\}. \tag{30}$$

[5]The symbol † denotes the conjugate transpose of a matrix.

[6]The identity matrix, **diag** $\{\cdots, 1, \cdots\}$, is denoted by $\boldsymbol{I}$.

TABLE I
NOISE PARAMETERS FOR IDEAL DIODE IN IDEAL SINGLE- AND DOUBLE-SIDEBAND EMBEDDING CIRCUITS

	SSB MIXER	DSB MIXER
Input noise temp. (referred to ω_1)	$T_M = \frac{\eta T}{2}\left[L_1 - 1\right]$	$T_M = \frac{\eta T}{2}\left[L_1 - 1 - \frac{L_1}{L_{-1}}\right]$
Input noise temp. (double sideband)	———	$T_{M_{DSB}} = \frac{\eta T}{2}\left[1 - \frac{1}{L_1} - \frac{1}{L_{-1}}\right] \div \left[\frac{1}{L_1} + \frac{1}{L_{-1}}\right]$
Mixer contribution to output noise temp.	$T'_M = \frac{\eta T}{2}\left[1 - \frac{1}{L_1}\right]$	$T'_M = \frac{\eta T}{2}\left[1 - \frac{1}{L_1} - \frac{1}{L_{-1}}\right]$
Mixer noise-temp.-ratio	$t_M = \frac{\eta}{2}\left[1 - \frac{1}{L_1}\right] + \frac{1}{L_1}$	$t_M = \frac{\eta}{2}\left[1 - \frac{1}{L_1} - \frac{1}{L_{-1}}\right] + \frac{1}{L_1} + \frac{1}{L_{-1}}$

The right side of (30) must be real,[7] so it is necessary only to consider the real parts in the summation. Hence,

$$\langle \delta V_{n_0}^2 \rangle = \eta k T \Delta f \frac{|Z_{e_0}|^2}{\mathrm{Re}\left[Z_{e_0}\right]} \cdot \left\{ 1 - 2\sum_m |Z'_{0m}|^2 \frac{\mathrm{Re}\left[Z_{e_m}\right]}{|Z_{e_m}|^2} \frac{\mathrm{Re}\left[Z_{e_0}\right]}{|Z_{e_0}|^2} \right\}. \quad (31)$$

From (22), the $m=0$ element of the summation is equal to $1/4$. Using (19), (31) can be written as

$$\langle \delta V_{n_0}^2 \rangle = \eta k T \Delta f \frac{1}{2} \frac{|Z_{e_0}|^2}{\mathrm{Re}\left[Z_{e_0}\right]} \left\{ 1 - \sum_{m \neq 0} \frac{1}{L_m} \right\}. \quad (32)$$

The shot-noise power delivered to the matched load Z_{e_0} is

$$P' = \langle \delta V_{n_0}^2 \rangle \frac{\mathrm{Re}\left[Z_{e_0}\right]}{|Z_{e_0}|^2} = \frac{\eta k T \Delta f}{2} \left\{ 1 - \sum_{m \neq 0} \frac{1}{L_m} \right\} \quad (33)$$

c.f., (4).

If the embedding network is at temperature T_E, thermal noise will be down-converted from each sideband to the (matched) IF load Z_{e_0}. The available noise power from the mixer diode at the IF port is then

$$P_{0_{\mathrm{avail}}} = k\Delta f \left\{ \frac{\eta T}{2}\left[1 - \sum_{m \neq 0} \frac{1}{L_m} \right] + T_E \sum_{m \neq 0} \frac{1}{L_m} \right\}. \quad (34)$$

By comparison with (5), it is clear that the available IF noise power from the mixer diode is equal to that at the output of a linear passive network having the following properties.

1) The physical temperature T_A of the network is related to that of the diode T by

$$T_A = \eta T/2. \quad (35)$$

2) The loss L_m between port m of the network and the output is equal to the corresponding conversion loss L_m of the embedded mixer diode for all m.

A. Noise Characterization of the Mixer Diode in Ideal Embedding Circuits

From (34), it is possible to derive the commonly used mixer noise parameters for the ideal mixer diode. However, it is clear that $P_{0_{\mathrm{avail}}}$ depends on the embedding impedance (and its temperature) at all sideband frequencies ω_m. For simplicity, only two embedding configurations will be examined here.

1) A single-sideband (SSB) mixer with reactive embedding impedances at all sidebands other than the upper sideband (ω_1) and IF (ω_0). It follows from (19) that $L_m \to \infty$ for $m \neq 1$.

2) A double-sideband (DSB) mixer with reactive embedding impedances at all sidebands other than the upper sideband (ω_1), lower sideband (ω_{-1}), and IF (ω_0). In this case, $L_m \to \infty$ for $m \neq \pm 1$.

Commonly used noise parameters are: 1) the equivalent input noise temperature T_M of the mixer, referred to one sideband, 2) the available output noise temperature T'_M of the mixer, evaluated with the input terminations (Z_e) at absolute zero temperature, and 3) the mixer noise-temperature ratio $t_M = P_{0_{\mathrm{avail}}}/kT\Delta f$ with the input terminations and the diode at $T_0 = 290$ K. Expressions for these quantities are given in Table I.

For radiometric applications, in which the ideal DSB mixer sees equal temperatures in the upper and lower sidebands, it is common to use a DSB equivalent input noise temperature $T_{M_{DSB}}$, and a DSB conversion loss L_{DSB}.

[7]That $\langle \delta V_{n_0}^2 \rangle$ must be real is evident from physical considerations. This can also be deduced mathematically from (20) using the fact that C is Hermitian: then for any vector V, $VCV^\dagger$ is real.

For the ideal DSB mixer,

$$L_{\mathrm{DSB}}=\left[\frac{1}{L_1}+\frac{1}{L_{-1}}\right]^{-1} \tag{36}$$

and

$$T_{M_{\mathrm{DSB}}}=T'_M L_{\mathrm{DSB}}$$

$$=\frac{\eta T}{2}\left[1-\frac{1}{L_1}-\frac{1}{L_{-1}}\right]\left[\frac{1}{L_1}+\frac{1}{L_{-1}}\right]^{-1}. \tag{37}$$

B. Comments on the Noise–Temperature Ratio t and Noise Figure

The noise–temperature ratio t_M of a mixer, as defined above, is an easily measured parameter, and, consequently, it is often quoted when describing mixer performance. Some confusion has existed between t_M for the mixer, and the noise–temperature ratio t_D of a dc-biased diode. It can be shown from (7)–(9) that, under dc bias, the available noise power from a diode at temperature T is $\eta kT\Delta f/2$, whence $t_D=\eta/2$. It is clear from Table I that, for the ideal mixers considered, $t_M \neq t_D$.

For the ideal SSB and DSB mixers considered here, the minimum possible conversion losses are [9], [14] 1 (0 dB) and 2 (∼3 dB). It follows from Table I that, in both cases, when operating with minimum conversion loss, $t_M \to 1$.

It is widely believed that the noise figure of a mixer is equal to its conversion loss. That this is not strictly true, even for the idealized two-and three-frequency mixers described above, can be shown easily using the equations in Table I. For many practical receivers, especially those in which the overall receiver noise is dominated by IF amplifier noise, the error in equating conversion loss and noise figure may be tolerable, but, in general, this rule should not be expected to give accurate results.

V. Conclusion

The ideal exponential diode, operating as a mixer, has been investigated using the analysis of Held and Kerr [10], [11]. The diode is assumed to exhibit full shot-noise, and is pumped by an arbitrary LO waveform. It has been shown that the diode is equivalent to a passive lossy multiport network having ports at all sideband frequencies at which (real) power flow can occur between the diode and its embedding. The physical temperature T_A of the network is related to that (T) of the diode by $T_A=\eta T/2$, which is in agreement with Dragone [8] and Saleh [9]. It follows that an SSB (DSB) mixer is accurately represented by a two-port (three-port) attenuator only if the diode is reactively terminated at all sidebands other than the signal and IF (and image).

Two common beliefs concerning the noise performance of diode mixers are examined and shown to be *generally incorrect*. These are: 1) that the noise–temperature ratio t_M of a pumped mixer is equal to the noise–temperature ratio t_D of the dc-biased diode, and 2) that the noise figure of a mixer is equal to its conversion loss. For the case of ideal SSB and DSB mixers, it is shown that, as the conversion loss approaches the theoretical minimum value (0 or 3 dB), the mixer noise–temperature ratio t_M approaches unity.

The attenuator noise model has application to Schottky diode mixers operating in the region from ∼1 MHz to several GHz, provided the diode has small series resistance and nonlinear capacitance, and the embedding (mount) impedance is well defined at frequencies up to several times the LO.

For mixer diodes with appreciable nonlinear capacitance, a more general analysis [10], [11] must be used to include the (parametric) effects of the time-varying capacitance acting on correlated components of the time-varying shot-noise. The more general analysis must also be used for diodes in which the relationship between the current-dependent noise and the diode current differs from the simple shot-noise equation (9).

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